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THERMAL GRADIENT-INDUCED DEFLECTION OF A THICK-WALLED CYLINDER WITH BENDING RESIDUAL STRESSES

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13. ABSTRACT *(Maximum 200 words)*
The interaction of a thermal gradient with bending residual stresses in a thick-walled cylinder is investigated using experimental measurements from prior work, mechanics analysis, and finite element stress analysis. A temperature gradient is applied to a cylinder containing residual stresses due to plastic bending resulting in transient elastic relaxation of the nonaxisymmetric residual stresses and bending of the cylinder. Analysis of the well-known similar problem in a rectangular bar is done first using solid mechanics solutions of ideal cases. Finite element calculations are made of the residual stresses following plastic bending of a thick-walled cylinder, the effects of a temperature distribution, and the resultant changes in stresses and strains and the associated tube bending. Results from the two approaches for a 200°C temperature gradient show a maximum angular displacement of 0.004 to 0.008 deg/m and the displacement returning to zero as the thermal gradient diminishes with time.

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TABLE OF CONTENTS

Tables

List of Illustrations

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INTRODUCTION

The dimensional stability of a thick-walled cylinder containing residual stresses is of concern, because thick-walled cylinders with significant overstrain stresses are often subjected to high pressures and elevated temperatures. Throop and coworkers (ref 1) measured the permanent closing of the inner radius of overstrained cylinders when subjected to elevated temperatures and varying amounts of temperature gradient. This prior work had general application to cannon and to other uses of cylinders that require dimensional stability.

The topic here is more specialized. It addresses the transient interaction of a thermal gradient with bending residual stresses in a thick-walled cylinder. The problem is sketched in Figure 1. If the cylinder were first bent beyond the plastic limit, a residual stress distribution of the type shown by the dashed lines could be produced. In general, tensile residual stress is present at locations that experienced compressive yielding during prior bending, and compressive residual stress is present at locations that experienced prior tensile yielding. Note that the residual stress distribution is not axisymmetric; of particular note, the stresses at opposite points of the inner surface are of the opposite sense. Then, when heat is applied to the inner surface, a transient elastic relaxation--due to reduced elastic modulus at elevated temperature--of the nonaxisymmetric residual stresses will cause bending of the cylinder. The amount of bending may be small, but for cannon applications, even a small amount of angular displacement of the cylinder can cause a significant deviation in the projectile position after it has traveled a large distance. The bending of the cylinder will be particularly bothersome, because it will appear and then disappear as the thermal gradient forms and then diminishes. This problem of the transient angular displacement of a previously bent cylinder subjected to thermal gradient is studied in the following paragraphs.

ANALYSIS

Temperature Effects on Modulus

The effect of test temperature on the elastic modulus of the steel alloy of interest is summarized first. ASTM A723 steel (ref 2) is commonly used for thick-walled cylinder pressure vessels such as cannon and reaction vessels for polymers, and both of these components are often subjected to elevated temperatures. Barranco (ref 3) was among the first to measure mechanical properties at elevated temperature for this type of steel, including measurements of modulus. More recent tests have been done with A723 steel (ref 4), and other similar alloys have been tested (ref 5). A summary of pertinent results is shown in Figure 2. All of the results, including the two sets of A723 data (refs 3,4) and the data for 4130 and 4140 steel, show a progressive decrease in modulus, E, with increasing temperature. A polynomial expression was fitted (by regression) to the two sets of A723 data, as follows:

$$E = 207 - 3.82\times10^{-2}\,T + 7.77\times10^{-5}\,T^2 - 4.45\times10^{-7}\,T^3 \qquad (1)$$

$$\textit{for } -50^\circ C \le T \le +650^\circ C\ ;\ E \textit{ in units of GPa}$$

Equation (1) provides a reasonable fit of the A723 data and also shows no significant divergence from the trend for similar steels. It is used in the upcoming analyses of angular displacement of bar and cylinder.

Rectangular Bar Analysis

The concepts used in calculating the angular displacement caused by the interaction of thermal gradient with bending residual stress can be illustrated by considering the classic Timoshenko (ref 6) bar problem. Figure 3 outlines the concepts. The residual stress resulting from plastic hinge bending of a rectangular bar is shown, where the maximum value, σ_o, is the yield strength of an ideal perfectly plastic

material. If a step temperature gradient is envisioned to proceed outward from the neutral axis of the beam, that is, x proceeds from 0 to H/2, then a modified residual stress distribution results. The key points are that the reduced elastic modulus at elevated temperatures causes the modified stress, and that the modified stress results in an unbalanced moment and an associated angular displacement of the bar.

Equations of solid mechanics describing these concepts were developed by writing expressions for the bending moment due to the bending residual stress distribution shown in Figure 3, following the general procedure of Timoshenko (ref 6). One expression, Eq. (2), describes the moments (designated as positive) from the bar neutral axis outward to the points where the residual stress is zero at $x/H = \pm 1/3$. Equation (3) is for the remaining moments. The nondimensional expressions for moment, M, as a function of relative position in the bar, x/H, are

$$M/\sigma_o bH^2 = [x/H]^3[1 + (1-3x/H)/(x/H)] \quad (2)$$
$$for\ 0 \leq \pm x/H \leq 1/3$$

$$M/\sigma_o bH^2 = [1/27 - (x/H-1/3)^2(2x/H + 1/3)] \quad (3)$$
$$for\ 1/3 \leq \pm x/H \leq 1/2$$

Note that both Eq. (2) and (3) reduce to Timoshenko's result, that is, $M/\sigma_o bH^2 = 1/27$ for $\pm x/H = 1/3$.

The second expression required for calculation of the thermal gradient-induced angular displacement of the bar is for the angular displacement as a function of the moment as modified by the gradient. This is obtained from the known relationship between moment and angle, Θ, (in degrees) for a beam (ref 7)

$$\Theta = 180\ My/\pi EI \quad (4)$$

where y is the length of beam over which the moment is applied, and I is the moment of inertia ($bH^3/12$). The total moment, M, is multiplied by a factor ($\Delta E/E$) to define the modified moment due only to the change in modulus with temperature

$$M' = (\Delta E/E)M \quad (5)$$

Values of ($\Delta E/E$) are easily obtained from Eq. (1). Then, the calculated angular displacement due to the thermal gradient-induced change in modulus is

$$\Theta = 180(\Delta E/E)My/\pi EI \quad (6)$$

Equations (2), (3), and (6) were used to calculate the angular displacement of a rectangular bar with similar configuration, residual stress, and temperature conditions as those used for thick-walled cylinder finite element calculations. A comparison of the two sets of results was made as an aid to understanding the nature of the effects and as a consistency check on the results.

<u>Cylinder Finite Element Analysis</u>

The finite element analysis modeled a thick-walled cylinder subjected to a complex history of bending and heating. The cylinder was 1.0 m long, had an inner diameter (ID) of 0.1 m, an outer diameter (OD) of 0.2 m, and the elastic modulus properties discussed in relation to Figure 2. The load and heating history included a constant applied bending moment that resulted in significant plastic

deformation and residual stress, relaxation to zero load, heating at the ID to produce a significant thermal gradient, and soak-out to a uniform elevated temperature. Changes in curvature of the 1.0-m long segment were monitored by observing the total angular displacement of the ends of the cylinder.

The heating problem was solved first using ABAQUS two-dimensional diffusion elements (DC2D8) in a mesh defining 192 elements on a symmetric half of the cross section of the cylinder. Heating on the ID from a hot gas was simulated using a film heat transfer coefficient of 500 J/m^2s and a gas temperature of 1000°C. The heat was applied for 120 seconds resulting in an ID temperature of 336°C and an OD temperature of 138°C. The heating was then stopped, and the cylinder was allowed to soak-out to a nearly uniform temperature of 187°C. The thermal solution was checked to ensure that the temperature distribution was symmetric about the cylinder axis and stored for use in the full structural problem. Structural analysis was performed using the same mesh as the thermal analysis, with the substitution of ABAQUS eight-node generalized plane-strain elements (CGEP10). This element type uses two global nodes to model the three degrees of freedom at the ends of the prism defined by the cross section mesh. One node defines the change of length of the prism, and the other node defines the two rotations at the end planes. In this study, the beam length was left free of constraint, one rotation was constrained to enforce the symmetry condition, and the second rotation was used to apply a constant bending moment in the bending phase of the analysis. This is also the degree of freedom that is plotted as angular displacement in the final results.

The full bending and heating analysis started with the cylinder at 20°C and proceeded in four steps:

1. a 10-second loading sufficient to produce plastic deformation;
2. a 10-second unloading to produce the appropriate nonsymmetric residual stress state;
3. a 120-second heating using temperature information from the thermal solution;
4. a 120-second soak-out using temperatures from the thermal solution.

This produced a total time for the full analysis of 260 seconds, which can be used as a basis for plotting the angular displacement of the ends of the cylinder. The level of the final residual stress was controlled by the maximum applied bending moment that was varied in five steps from 0.4 to 0.6 MNm. The solution at 0.4 MNm was completely elastic. The remaining four solutions are shown as plots of angular displacement versus time in the upcoming results.

RESULTS

Bar Results

Example temperature and residual stress distributions from the cylinder analysis and the corresponding stress and temperature input values for the bar analysis are shown in Figure 4. The cylinder results are for a prior bending moment of 1.2 MNm and for the temperatures at the point 140 seconds into the 260-second long bending and heating cycle. The temperature difference between ID and OD at this point was a ΔT of 198°C. For comparison, ΔT values of 90°C to 230°C (depending on forced air or water cooling on the OD) were measured in tests of A723 cylinders (ref 1). Note that the value of residual stress at the ID of the cylinder, -230 MPa, is much below the yield stress of the A723 steel used in the cylinder model, 1122 MPa. The value of -230 MPa was used in the bar analysis, along with the two-step thermal gradients shown as dashed lines--one based on the average temperature over the inner two-thirds of the wall from the cylinder analysis (240°C), and the other based on the ID temperature from the cylinder analysis (336°C).

Angular displacement calculations for the bar are shown in Figure 5 for three arbitrary step temperature distributions and for the step distributions shown in Figure 4 that approximate the tube conditions. Equations (2) through (5) were used, with σ_o = ± 230 MPa, H = 0.2 m, y = 1.0 m, and ΔE/E values from Eq. (1) for the temperatures shown in Figure 5. Several points should be noted. First, the angular displacement increases to a maximum (at x/H = 1/3) and then returns to zero as the gradient goes to zero. Second, the angular displacement becomes progressively larger at higher temperatures due to the progressive decrease in modulus at higher temperatures, as seen in Figure 2. Finally, the relationship of the various results in Figure 5 can be explained by the ΔE/E values from Eq. (1) used to calculate the results; the maximum displacement angles are directly related to the ΔE/E values, as shown in Table 1.

Table 1. Rectangular Bar Temperature Distribution Results

Step Temperature Distribution (°C)	ΔE/E	Maximum Displacement (deg/m)
T1 = 100; T2 = 0	0.017	0.0024
T1 = 200; T2 = 0	0.039	0.0055
T1 = 300; T2 = 0	0.080	0.0113
T1 = 240; T2 = 145	0.028	0.0040
T1 = 336; T2 = 145	0.049	0.0070

Cylinder Results

A summary of results for the cylinder bending portion of the finite element analysis is shown in Table 2. The expected rapid increase in residual displacement and residual stress, once plastic deformation begins, can be seen. Note that the total bending displacement for M = 0.8 MNm in Table 2, 3.02 deg/m, agrees well with Θ = 3.00 deg/m, the value calculated from Eq. (4) using y = 1 m, E = 207 GPa, and I = π(OD4 - ID4)/64, with OD = 0.1 m and ID = 0.05 m. Thus, the finite element results and the results from standard equations of solid mechanics agree within one percent. The total displacements due to plastic bending and subsequent heating are plotted in Figure 6. This figure gives a macroscopic view of the full cylinder analysis from a virgin cylinder to uniformly heated one. The four curves represent different residual stress states with the initial loading and unloading to a residual deformation clearly shown. However, note that during the longer heating and soak-out phase, there appears to be no change in angular displacement. However, if the residual displacement is subtracted from the total displacement and the resulting data is replotted on a highly expanded scale, a microscopic view of the angular displacement during the thermal phases can be seen (see Figure 7). In this plot, the angular displacement increases during heating and falls off during soak-out. These curves are smooth but somewhat wavy, which is probably the result of the interaction of the nonlinear heating process with the nonlinear variation of Young's Modulus. It should be noted that the data for this plot must be generated in full double precision and that data of this quality are not available in the standard ABAQUS printout. These results came from displacement information written to an ABAQUS results file and processed using double precision arithmetic.

Table 2. Cylinder Bending and Residual Stress Results

Bending Moment (MNm)	Maximum Total Displacement (deg/m)	Maximum Residual Displacement (deg/m)	Maximum Residual Stress (MPa)
0.8	3.02	0.000	0
0.9	3.41	0.014	92
1.0	3.90	0.125	218
1.1	4.61	0.459	349
1.2	5.94	1.419	476

It is interesting to compare the angular displacement results of Figure 5, the idealized bar results, with those of Figure 7 for the cylinder. Both results show the angular displacement due to thermal gradient increasing to a maximum and then diminishing to zero, but the values of displacement are somewhat different. The bar analysis using temperatures that approximate those of the cylinder gave Θ = 0.0040 and 0.0070 deg/m for an average temperature and the ID temperature, respectively; whereas the cylinder analysis gave Θ = 0.0084 deg/m for the corresponding moment (1.2 MNm) and the complete cylinder temperature distribution. The difference in Θ may be due to the configurational differences between the bar and the cylinder.

SUMMARY AND CONCLUSIONS

The overall result is the demonstration of a small transient bending effect in a plastically bent cylinder when a thermal gradient exists, with the cylinder returning to its original shape when the temperature returns to a uniform condition. This effect is only seen when the variation of elastic modulus with temperature is included in a mechanics analysis. The magnitude of the effect would not be important in most practical problems. However, the accuracy requirements of any precision gun system require extremely close attention to the pointing accuracy of the gun.

The following are the specific results:

1. Published measurements of elastic modulus from -50°C to +650°C were characterized for use in structural mechanics analysis at elevated temperature.

2. Interaction of the bending residual stresses in a rectangular bar with a step thermal gradient results in transient bending of the bar that approximates the bending calculated for a thick-walled cylinder under similar conditions.

3. Finite element analysis of plastic bending of a thick-walled cylinder followed by application of a thermal gradient results in transient bending of the cylinder: a ΔT of 198°C between ID and OD resulted in a maximum angular displacement of the cylinder of 0.0084 deg/m.

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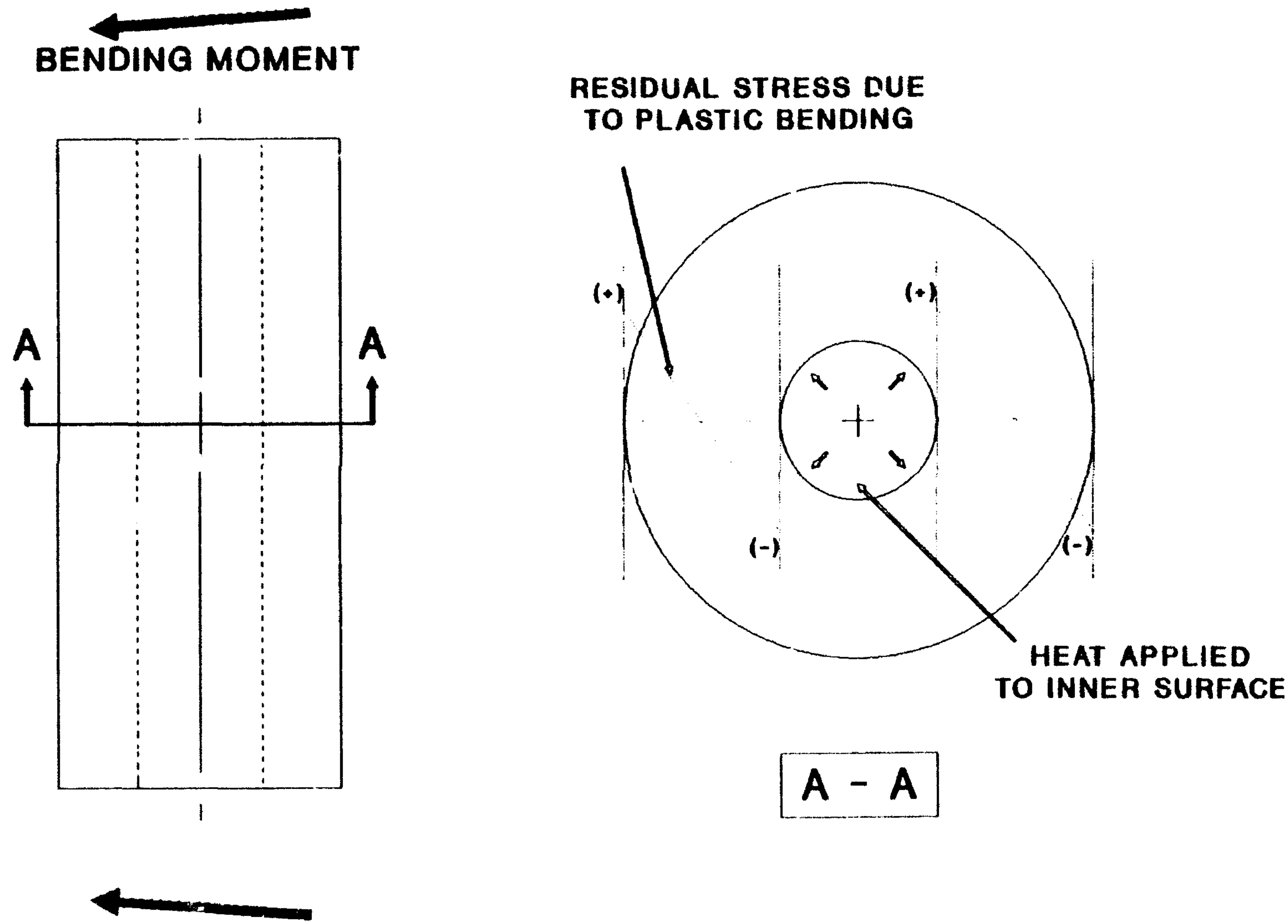

Figure 1. Thermal load applied to cylinder with bending residual stress.

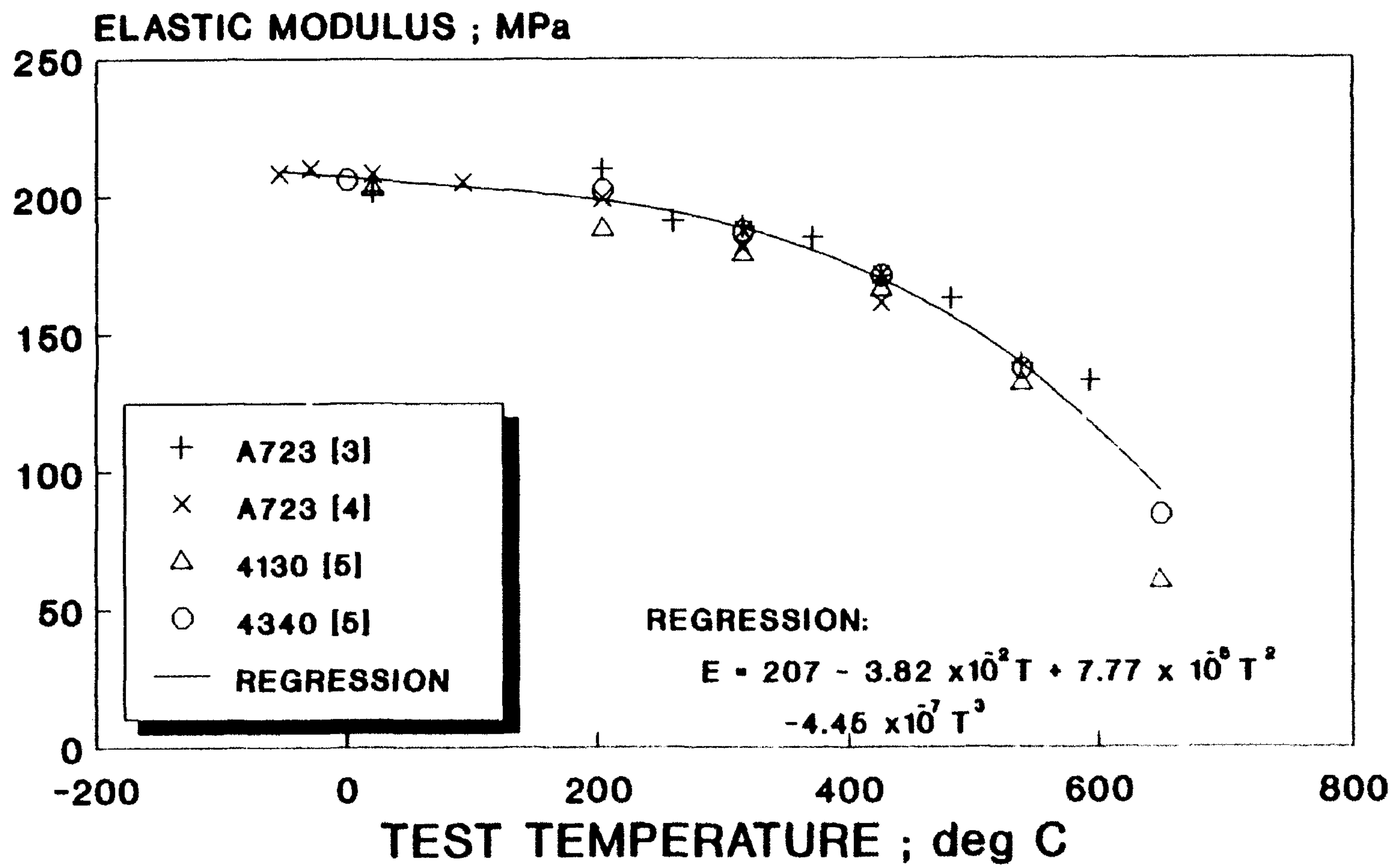

Figure 2. Variation of elastic modulus with temperature for various steels.

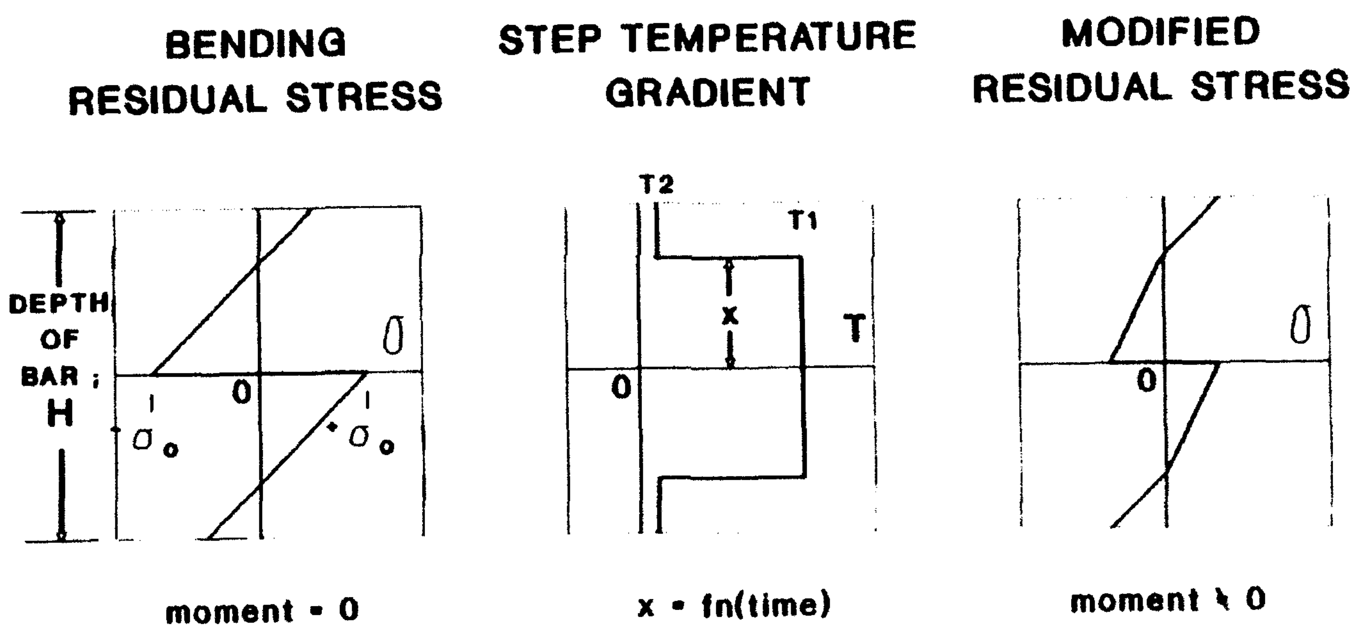

Figure 3. Thermal gradient applied to rectangular bar with ideal residual stresses.

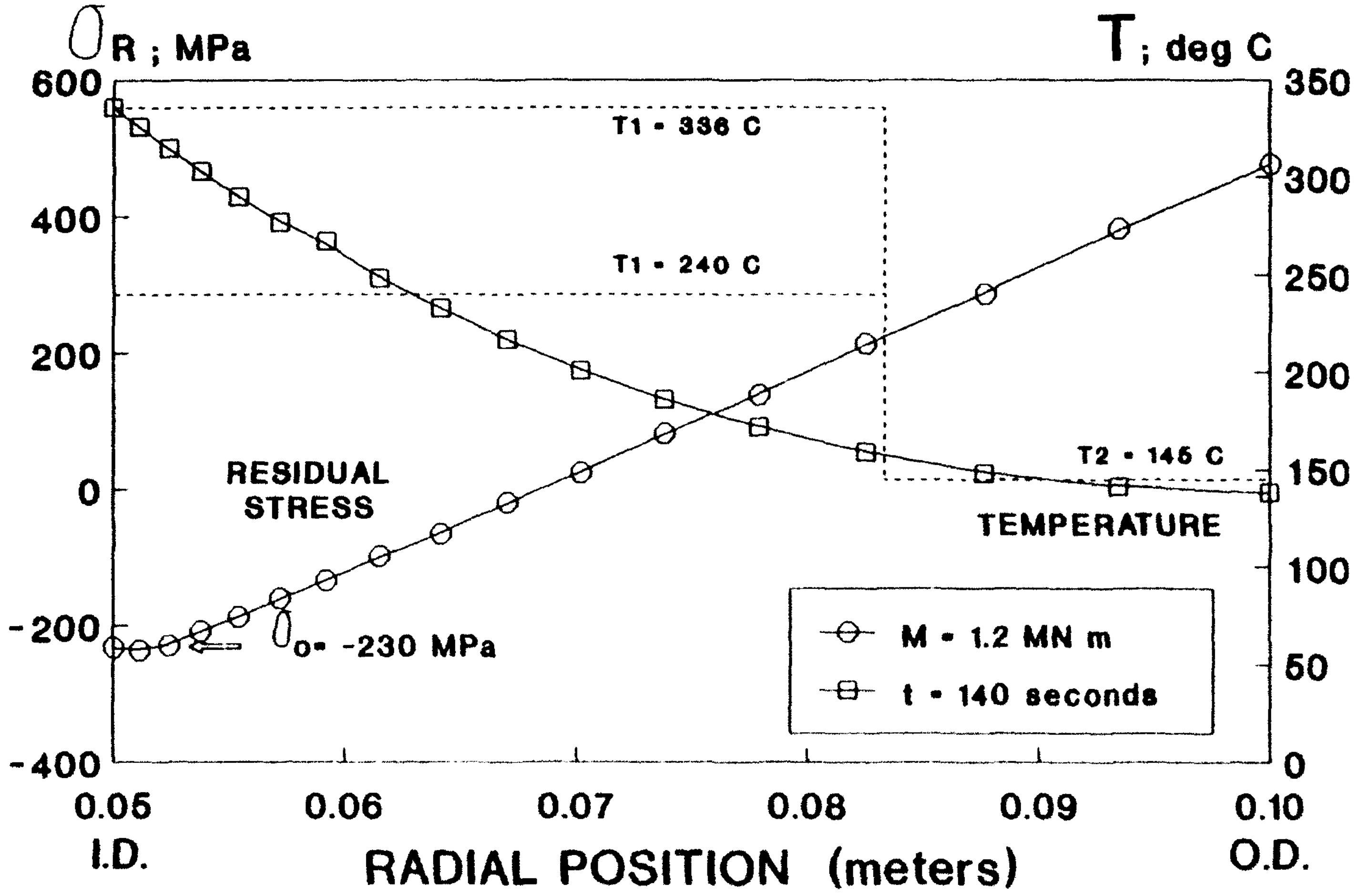

Figure 4. Residual stress and temperature distributions for cylinder and bar.

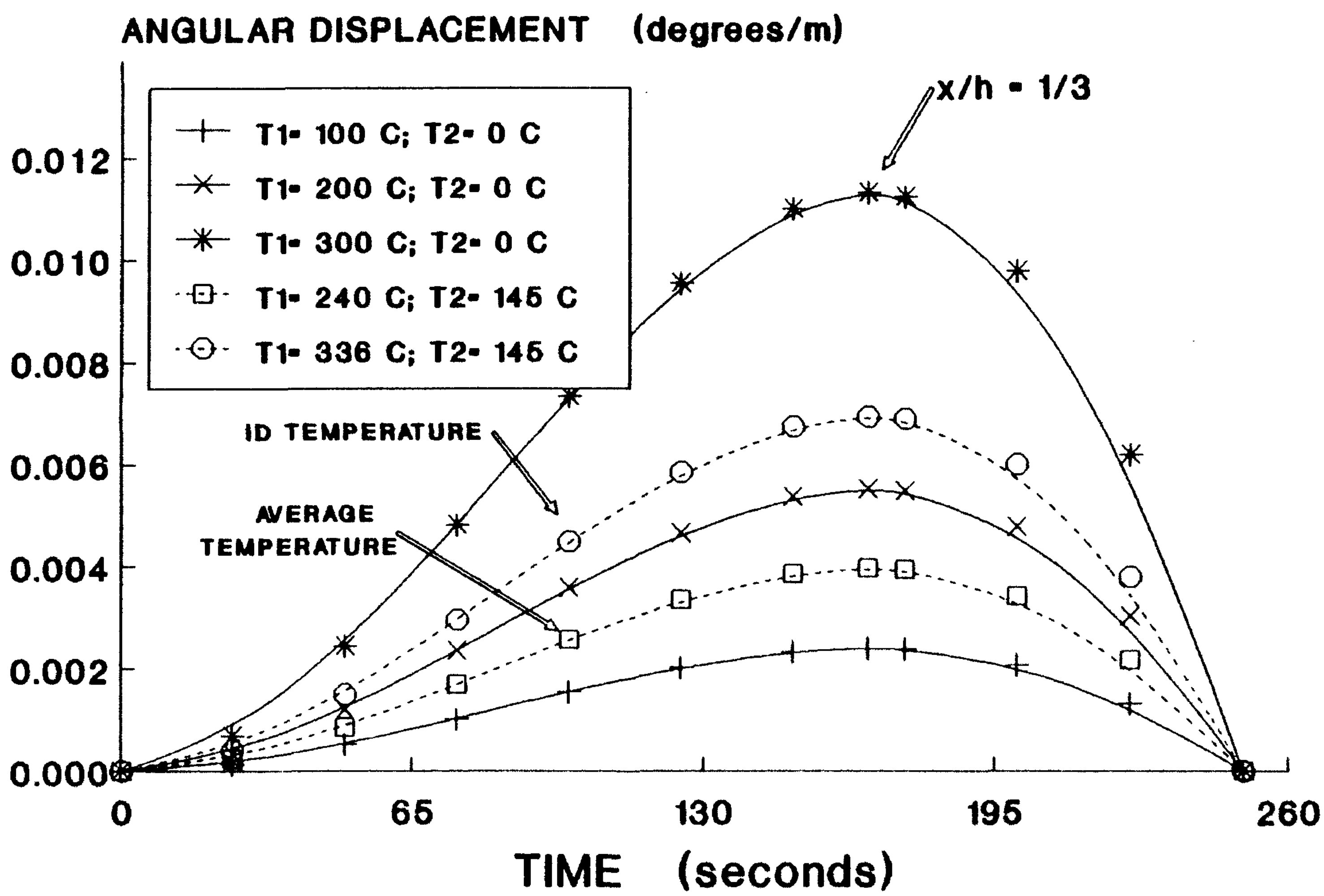

Figure 5. Change in angular displacement for bar due to moving step thermal gradient.

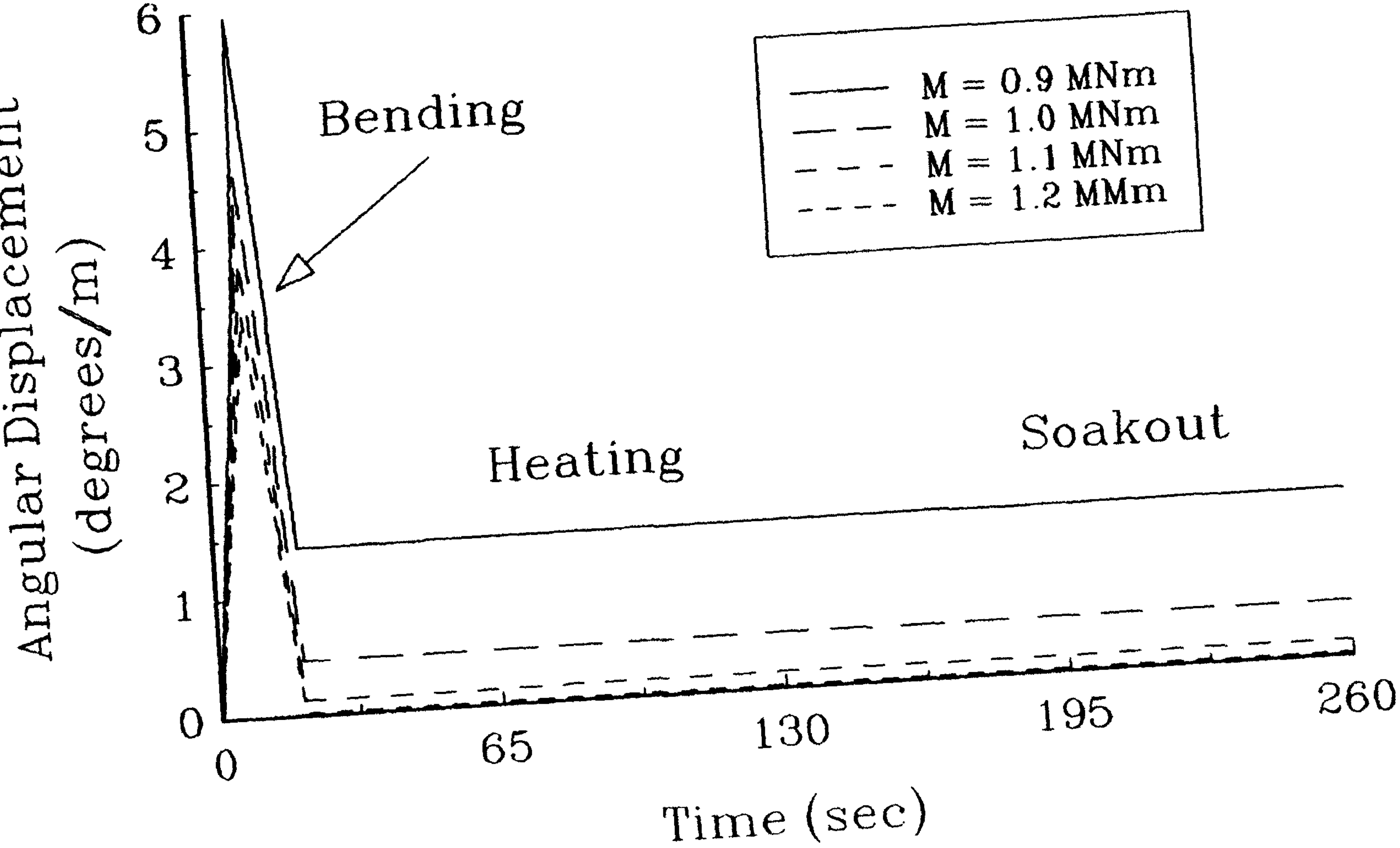

Figure 6. Macroscopic view of angular displacement due to plastic bending and heating of cylinder.

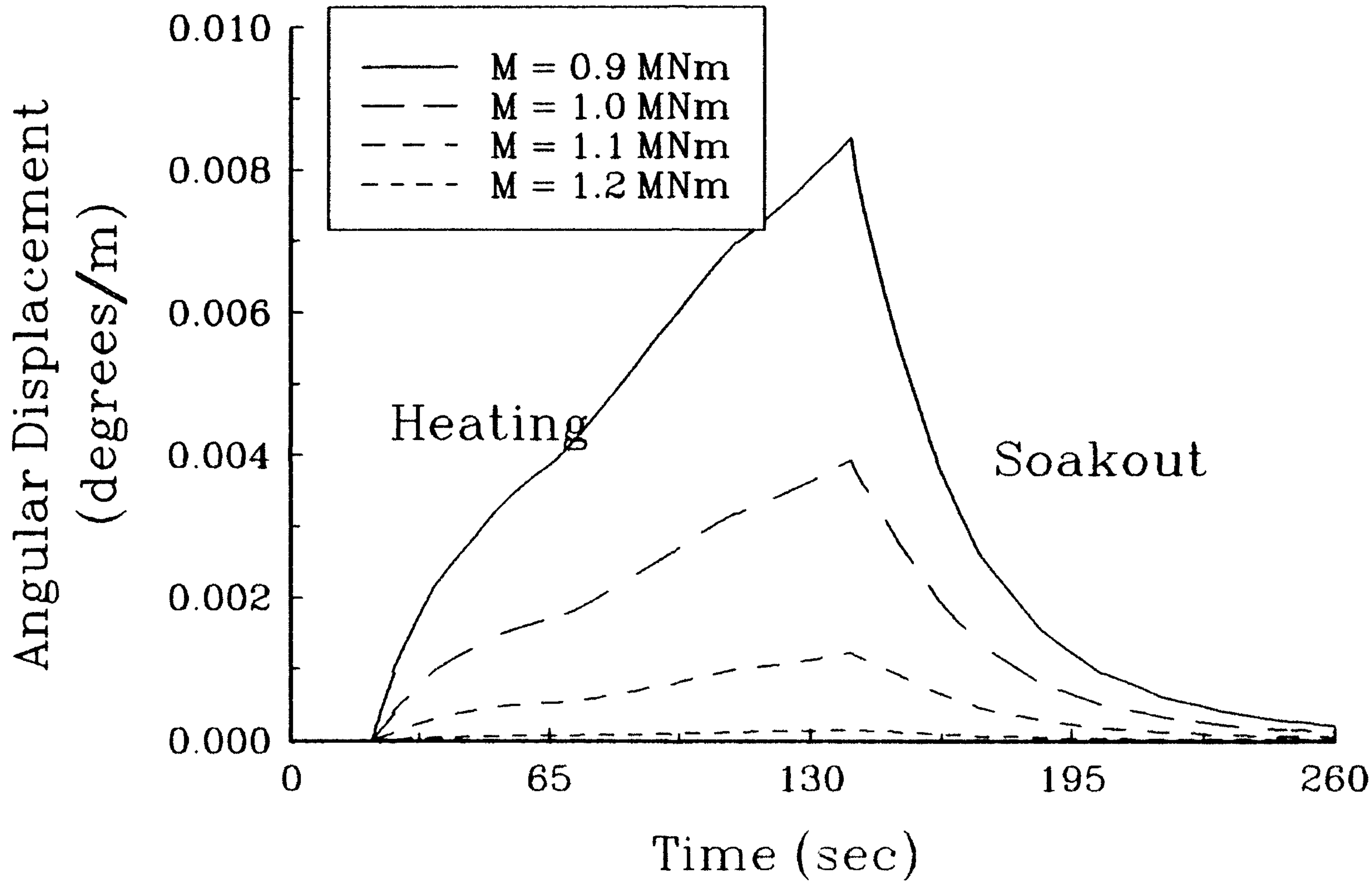

Figure 7. Microscopic view of angular displacement due to plastic bending and heating of cylinder.

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